Robust HEMT Microsensors as Prospective Successors of MOSFET/ISFET Detectors in Harsh Environments

HEMT Microsensors

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Abstract

The reliable operation of wide-bandgap HEMT (High Electron Mobility Transistor) devices at elevated temperatures up to 400°C, along with their less vulnerability to thermal or optical excitation, combined with their greater resistance to chemical corrosion by acids and alkalis, has encouraged researchers to make endeavours towards the development of a family of sensors for harsh environments, an area where conventional silicon MOSFET (metal-oxide-semiconductor field-effect transistor) and ISFET (ion-sensitive field-effect transistor) devices are rendered ineffective. Additionally, the close proximity of the conducting 2DEG (two-dimensional electron gas) HEMT channel to the surface provides enhanced sensitivity to adsorption of substances, while the miniaturization and high-frequency operation capability of HEMT-based microsensors enables their seamless integration into wireless sensor networks for remote monitoring of patient's health through bedside or handheld instrumentation. This paper reviews the recent progress of HEMT-based microsensors for physical, chemical and biological applications, describes the challenges faced, and also points out the future trends and opportunities in this field. The notable HEMT sensing devices include physical sensors for pressure, stress and magnetic field measurements, and for terahertz detection; chemical sensors for pH, ammonium, potassium, mercury and other ions; oxygen, hydrogen, chlorine, HCl vapor, and other gases; biosensors for glucose, lactic acid, uric acid, DNA, prostate and breast cancer markers, kidney injury molecule-1, perkisus marinus, botulinum toxin, and various other analytes.

Keywords

HEMT; Microsensors; MOSFET; ISFET; AlGaN/GaN; Physical Sensor; Chemical Sensor; Biosensor; Harsh Environments

Introduction

The word 'HEMT' brings to mind the thought of a high-frequency, high-power device used in microwave telecommunications. Another application of HEMT, which is no less important, but often overlooked, is 'sensor technology'. These two vital applications of HEMT form a bridge, linking the patient at home with the doctor in a far-off clinic or hospital, or other similar industrial automation equipment. One more feather in the cap of HEMT devices is their capability to withstand hostile or aggressive environments. The aforesaid qualifying features of HEMTs, along with their non-toxicity to living cells, have enabled HEMT-based microsensors to carve a unique niche for themselves, penetrating in applications where silicon devices have hitherto failed (Pearton et al. 2004, Chu et al. 2010a, Pearton and Ren 2013, Pearton et al. 2013). This paper aims to survey the recent advances in HEMT-based microsensors, which will play a pivotal role in future electronic control instrumentation, ranging from automotive electronics to aeronautics, aerospace engineering and oil drilling

Competition between HEMT-Based Microsensors and Silicon MOSFET/ISFET Microsensors

In silicon technology, the competitive devices against HEMTs are MOSFETs and ISFETs (Bergveld 1970, 2003 a,b). A vast plethora of MOSFET-based sensing devices have been reported. MOSFET pressure sensor is based on the MOSFET stress sensitive phenomenon, in which the drain-source current changes in accordance with the stress in the channel region (Zhang et al. 2006), or square and cross-shaped P-channel MOSFET directly integrated on the silicon diaphragm (De Sagazan et al. 2011). Fernández-Bolaños 2006 described a pressure sensor based on a suspended-gate MOSFET (SG-MOSFET) using a polyimide process with SOI (silicon-on-insulator)

wafer (Fig. 1).

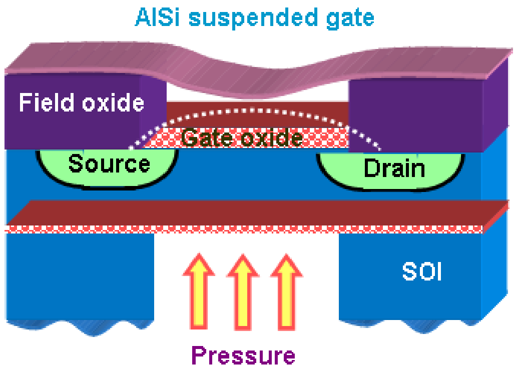

FIG. 1 SUSPENDED-GATE MOSFET PRESSURE SENSOR

MOSFET strain sensor works on the drain-source current change with applied strain (Aoyagi and Izutani 2006). The MOSFET Hall sensor is a semiconductor resistor whose active thickness undergoes modulation on applying potentials to the top and bottom gates of the field-effect structure (Dolgiy et al. 2012). THz detection has been demonstrated by Stillman et al. 2007 using silicon CMOS (Complementary metal-oxide semiconductor) arrangement, consisting of P-channel and N-channel MOS transistors. MOSFET hydrogen sensor is based on the work function changes of the catalytic hydrogen-sensitive metal gate electrode, e.g., palladium, on hydrogen gas exposure (Gu et al. 2012).

ISFETs serve as platforms to fabricate a diversity of chemical and biosensors used in medical diagnostics, agriculture, food processing, pharmaceutical and chemical industries, besides their main application in pH sensing (Khanna 2007, 2011). Notable examples are chemical sensors for alkali ions, lead, mercury, ammonium, fluoride, phosphate and nitrate ions, and biosensors for glucose, urea, creatinine, triglycerides, etc. Fig. 2 shows the diagrammatic representation of ISFET device.

MOSFETs, ISFETs and HEMTs are all essentially field-effect transistors. But there is a basic difference in the process of creation of the channel. In MOSFETs and ISFETs, the channel is produced by ion implantation/diffusion (normally-ON devices) or induced by applied gate voltage through inversion layer formation (normally-OFF devices). As the channel is formed in a doped region, scattering of electrons with impurity ions reduces the carrier mobility and raises the noise level. Consequently, high-frequency operation is hindered, transconductance is low and signal-to-noise ratio is decreased. In HEMTs, the key element is a heterojunction formed between two semiconductor materials of different energy gaps. Electrons are transferred from the semiconductor with higher conduction band edge E_C to the one with lower E_C, where they can reside in a lower energy state, thereby forming the channel. Thus the channel is not formed in a doped semiconductor, so that impurity scattering does not occur. As a result, the noise level is suppressed and carrier mobility is high. Naturally, both the signal-to-noise ratio and carrier mobility are enhanced. The transconductance is also high. An exponential relationship exists between the charges on the gate surface and those in the channel. These properties favour the increase in sensitivity and lowering the detection limit of the HEMT-based sensors as compared to MOSFET or ISFET-based devices.

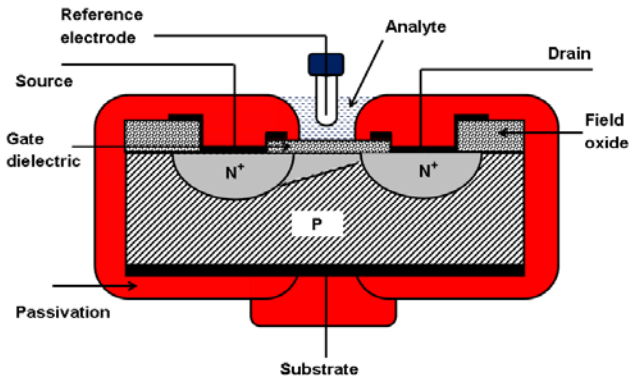

FIG. 2 SCHEMATIC DIAGRAM OF ISFET

In ISFETs, the gate insulators are sensitive to charging effects, and a reference electrode is required to bias the gate above the threshold voltage to allow the majority carriers to travel across the channel thus formed. Contrarily, HEMTs do not require a gate voltage to turn ON and therefore no reference electrode is necessary for operation, which is a significant advantage over silicon ISFETs, in addition to higher chemical and thermal stability of HEMTs.

Construction of a HEMT-Based Microsensor and Its Representative Fabrication Process

The HEMT-based microsensor (Fig. 3) comprises the HEMT structure and the functionalization layer to make it selective to specific species or parameters. The HEMT structure (Wang 2007, 2008; Thapa 2012) typically consists of a sapphire (or silicon or 4H-SiC) substrate, an undoped GaN buffer layer (typically 2-3 μm thick), an AlGaN spacer layer (20 A° thickness), and a Si-doped GaN cap layer (200 A° thickness). The cap layer, not shown in the figure, reduces the surface states and provides a homogeneous surface chemistry for functionalization, as well as improves the ohmic

contacts for source and drain without adversely affecting the Schottky contact.

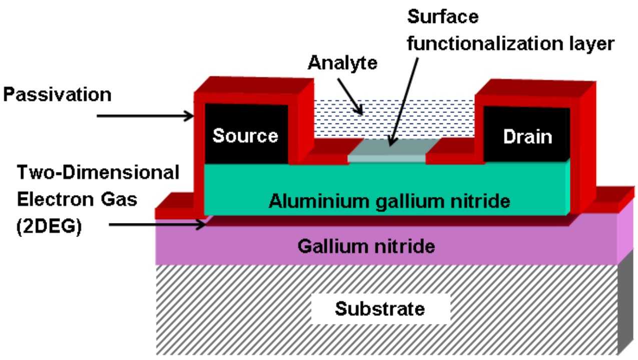

FIG. 3 THREE-DIMENSIONAL VIEW OF HEMT MICROSENSOR

The epitaxial layers are grown by molecular beam epitaxy (MBE) or metal-organic chemical vapour deposition (MOCVD). Mesa isolation is performed by inductively-coupled plasma etching. For ohmic contacts, Ti/Al/Pt/Au metallization is done by electron-beam evaporation with the pattern defined by lift-off process. The contacts are annealed at 850°C for 45 s. For Schottky contact, Ni/Au is deposited by sputtering. The source and drain regions are encapsulated using polymethyl methacrylate (PMMA). Only the gate area is left exposed for interaction with the analyte. Polydimethylsiloxane (PDMS) and polyimide are also used as encapsulants. The exposed gate area may be either gold-coated or left unmetallized. It is subsequently coated with the appropriate functionalization layer, depending on the intended application.

HEMT-Based Physical Sensors

Pressure Sensor

The changes in the capacitance of the channel of an AlGaN/GaN HEMT membrane structure fabricated on a Si substrate were measured by Kang et al. 2005.

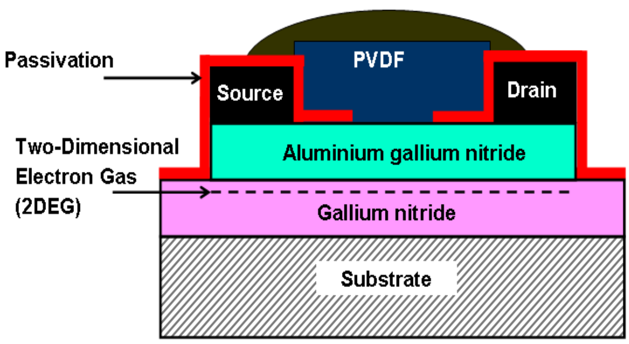

FIG. 4 HEMT PRESSURE SENSOR

Hung et al. 2009 coated the gate region of an AlGaN/GaN HEMT with PVDF film (Fig. 4) using an inkjet plotter, polarized the PVDF film by the application of a high voltage (10 kV at 70°C) between a copper electrode located 2 mm above the film and the grounded chuck on which the HEMT was mounted, and subjected the polarized PVDF-gated HEMT to pressure changes from 1 atm to 1 psi. They observed appreciable variations in channel conductance of HEMT, indicating its usability to measure small pressure differences ~ 1 psi.

The electromechanical behavior of a sapphire/GaN-based diaphragm structure was studied by Edwards et al. 2010. Brezeanu et al. 2011 revealed a HEMT sensor for measuring pressures in harsh environments.

Strain Sensor

Piezoresistance of $Al_{0.3}Ga_{0.7}N$/GaN HEMT channel was investigated by Yilmazoglu et al. 2006, who measured a gauge factor between 19 and 350 under defined biasing conditions. Thus HEMTs are employed as strain sensing elements.

The performance of GaN HEMT device for the induced strain was analytically modeled by Eliza et al. in 2010.

Hall Magnetic Field Sensor

AlGaN/GaN HEMT-based micro HEMT-based sensors exhibit stable operation from room temperature to 400°C with current-related magnetic sensitivity of 77 $VA^{-1}T^{-1}$ (Koide et al. 2012).

Terahertz Sensor

Lü and Shur 2001 demonstrated AlGaAs/GaAs terahertz HEMT detector operated at 2.5 THz and reported a regime of operation of such HEMT terahertz detectors that allowed them to increase the responsivity by more than an order of magnitude. Fatimy et al. 2006 fabricated ultra-short-gate (50 nm) InGaAs/InP devices and observed efficient THz detection. Watanabe et al. 2013 investigated dual-grating-gate (DGG)-HEMT structures for broadband detection of THz radiations, and showed ultra-sensitive THz imaging with the InP-based asymmetric DGG-HEMTs. Esfhani et al. 2013 reported changes in channel conductance for potential applications in chip-scale frequency-agile detectors, scalable to mid-THz frequencies.

HEMT-Based Chemical Sensors

pH Sensor

Ungated AlGaN/GaN HEMTs with Sc_2O_3 gate dielectric show a change in drain-source current of 37 μA for each decade pH variation in the pH range 3 to 8, with a resolution of 0.1 pH (Kang et al. 2007).

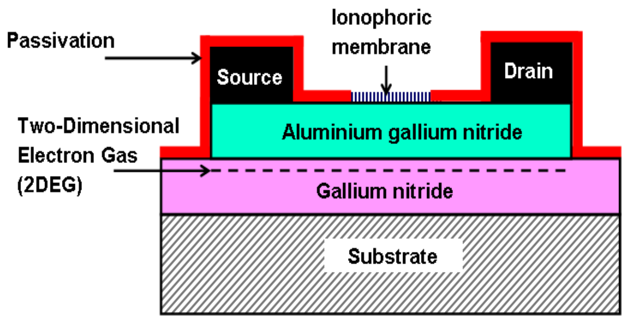

FIG.5 HEMT POTASSIUM ION SENSOR

The sensing response of an open-gated pH sensor fabricated on an AlGaN/GaN HEMT structure was investigated by Abidin et al. 2011. High sensitivity of 1.9 mA/pH at drain-source voltage = 5 V was obtained.

Potassium Ion CHEM HEMT

Valinomycin-doped PVC membrane (Fig. 5) deposited on the non-metallized gate of AlGaN/GaN HEMT helped in achieving a K^+-ion sensitivity of 52.4 mV/pK^+ in the concentration range 10^{-5} to 10^{-2} M with a lower detection limit of 3.1×10^{-6} M (Alifragis et al. 2007a). The drain-source current increased linearly with log [K^+].

Mercury (II) Ion Sensor

Wang et al. 2007 detected Hg^{2+} ions in as low as 10^{-7} M concentrations using bare Au-gated and thioglycolic acid functionalized AlGaN/GaN HEMTs. The latter sensors had 2.5 times larger sensitivity than the former, and also responded in <5 s. Selectivity of mercury detection over sodium or magnesium ions was >100.

Nitrate Ion Sensor

A plasticized PVC-based membrane containing a nitrate–selective ionophore was deposited on the HEMT gate (Myers et al. 2012), resulting in a nitrate ion sensor with a working range from 1×10^{-6} to 1×10^{-2} M, and a lower detection limit of 1×10^{-7} M.

Chloride Ion Sensor

AgCl thin film on ZnO-nanorod gated AlGaN/GaN HEMT could detect up to 10^{-8} M concentration (Chu et al. 2010b).

Ammonium Ion Sensor

HEMT device with non-metallized gate and coated with nonactin-enriched PVC membrane showed sensitivity of 55.5 mV/pNH_4^+ to ammonium ions in the range 10^{-5} to 10^{-2} M (Alifragis et al. 2007b).

Oxygen Sensor

Indium zinc oxide (IZO)-gated AlGaN/GaN HEMTs showed a strong response to the oxygen gas at 120°C; in addition, IZO was deposited by cosputtering from ZnO and In_2O_3 targets (Wang et al. 2010).

Hydrothermally-grown SnO_2 gate electrode with AlGaN/GaN HEMT sensor provided detection of 1% oxygen in nitrogen at 100°C (Hung et al. 2012a)

Hydrogen Sensor

Pd/Oxide/$Al_{0.24}Ga_{0.76}As$ HEMT-based sensor (Cheng et al. 2006) showed low hydrogen detection limit (4.3 ppm H_2/air) with a short response time.

Hung et al. 2012b synthesized SnO_2 dispersion by hydrothermal method, deposited it selectively on Au gate of HEMT by photolithography, and annealed it at 200-400°C. They studied the time dependence of the sensitivity on cycling between 1% H_2 in N_2 and pure N_2 gas at temperatures of 150°C, 200°C and 300°C. Fast and reversible hydrogen sensing was observed at low temperature.

Guo et al. 2013 reported an AlGaN/GaN HEMT-based hydrogen sensor which showed response variation of 25.8% upon 10-fold change of hydrogen concentration at 130°C.

Cl_2 gas and HCl Vapor Sensor

HEMTs are used for detecting corrosive, caustic chemicals. Exposure of Pt-gated HEMT to an oxidizing gas (1% Cl_2 gas) resulted in an increase in drain-source current I_{DS} whereas its exposure to a reducing gas (1% HCl vapour) caused a decrease in drain-source current (Son et al. 2011), showing the ability of HEMT to differentiate between oxidizing and reducing agents. Cl_2 gas withdraws electrons from the Pt-gate leading to a less negative effective gate voltage and producing a larger I_{DS}. The HCl vapour has the opposite effect.

HEMT-Based Biosensors

DNA Sensor

Thapa et al. 2012 fabricated a highly specific HEMT DNA sensor by immobilizing amine-modified single strand DNA upon the self-assembled monolayers of 11-mercaptoundecanoic acid on the Au gate. The

drain-source current decreased by about 100 μA at 1 V bias, when hybridization with complementary DNA took place.

Makowski et al. 2013 developed Au nanoparticle/HEMT sensors for detection of analytes such as specific DNA sequences, proteins, or other metabolites. Au NPs provide a proven system for detection of such analyte-receptor interactions.

Glucose Sensor

Glucose oxidase enzyme was immobilized on zinc oxide nanorod-gated HEMT (Chu et al. 2010b). The sensor could detect glucose concentrations from 0.5 nM to 125 μM in pH=7.4 buffer in <5 s.

Lactic Acid Sensor

ZnO nanorods were grown on the gate of the HEMT to provide a large surface area with a high surface-area-to volume ratio (Chu et al. 2008). Lactate oxidase enzyme was immobilized on the nanorod array. The biosensor could detect lactic acid from 167 nM to 139 μM.

Uric Acid Sensor

Song et al. 2012 constructed uric acid biosensor by uniformly distributing ZnO nanotetrapods on the HEMT gate and immobilizing uricase enzyme upon it. This sensor could detect uric acid concentrations from 0.2 nM to 0.2mM with the detection limit of 0.2 nM.

c-erb-2 (Breast Cancer Marker) Sensor

Antibody was attached to the Au-gated HEMT (Fig. 6) through immobilized thioglycolic acid (Chen et al. 2008). When c-erb-2 antigen was introduced, the drain-source current decreased in <5 s. The change was nonlinearly related to the antigen concentration. The detection range was from 16.7 to 0.25 μg/ml.

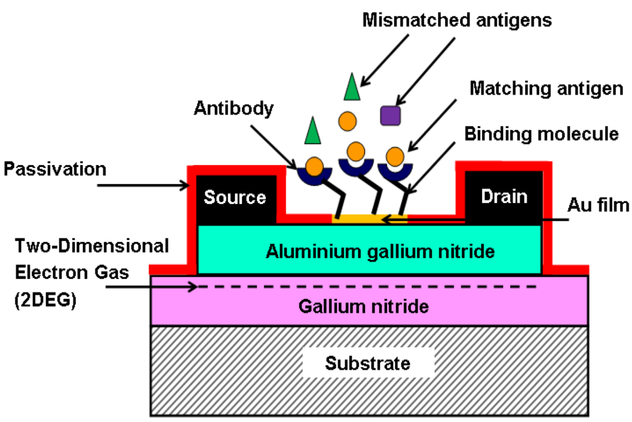

FIG. 6 HEMT c-erb-2 SENSOR

Prostate specific Antigen (Prostate Cancer Marker) Sensor

PSA antibody was fixed to the Au-gated HEMT through carboxylate succinimdyl ester bonds with immobilized thioglycolic acid (Kang et al. 2007). After PSA incubation, the drain-source current decreased with a detection limit of 10 pg/ml. PSA concentrations up to 1 μg/ml were measured, and the response time was less than 5 s.

KIM-1 (Kidney Injury Disease Biomarker) Sensor

A self-assembled monolayer of thioglycolic acid was absorbed on the Au gate of the HEMT (Wang et al. 2007). Kidney injury molecule-1 (KIM-1) antibody was immobilized through reaction between amine group of the antibody and carboxyl group of thioglycolic acid. On exposure to KIM-1, the drain-source current changed, and the change was nonlinearly proportional to KIM-1 concentration. The detection limit was 1 ng/ml in PBS buffer.

Perkisus Marinus Sensor

The antibody coating of the protozoan pathogen was applied on the thioglycolic acid immobilized on Au-gated HEMT (Wang et al. 2009). The presence of P. Marinus in water was seen through drain-source current changes within 5-20 s.

Botulinum Toxin Sensor

Botulinum toxin was detected in the range from 1 to 10 ng/ml by botulinum antibody functionalized Au-gated HEMT (Wang et al. 2008).

Discussion and Conclusions

A wide spectrum of HEMT-based microsensors has been demonstrated at laboratory level, a few of which are presented in Table-1. These HEMT-based microsensors represent a new generation of sensors which are potential successors to silicon MOSFET/ISFET sensors. Their capability to operate without reference electrode makes their usage possible with small volumes of analytes, and hence the experimental arrangement is considerably simplified. In opposition to this, ISFET devices have not been able to utilize the miniaturization benefit provided by solid-state technology because the bulky reference electrode is mandatory, and no reliable microelectrode substitute is still available.

TABLE 1 HEMT-BASED MICROSENSORS AT A GLANCE

Sensor category	Sensed quantity	Gate Surface	Surface coating	Transduction mechanism	References
HEMT-based physical sensors	Pressure	PVDF film	None	Changes in the charge of polarized PVDF film	Hung et al. 2009
	Strain	----------	---------	Variation in 2DEG channel conduction by external forces	Yilmazoglu et al. 2006
	Magnetic field	Cross pattern of Ti/Al/Ni/Au electrodes	None	Hall voltage generation from magnetic field between probes on AlGaN/GaN heterostructure having 2DEG at the heterointerface.	Koide et al. 2012
	Terahertz waves	----------	---------	Rectification of plasma waves	Lü and Shur 2001; Fatimy et al. 2006; Watanabe et al. 2013
HEMT-based chemical sensors	pH	AlGaN	Sc_2O_3	Action between polarization-induced surface charges and ions in the electrolyte	Kang et al. 2007
	Potassium ion	GaN cap	Valinomycin-doped PVC	Selective binding of K^+ ions to valinomycin	Alifragis et al. 2007a
	Mercury ion	Au	Thioglycolic acid	Chelation	Wang et al. 2007
	Nitrate ion	GaN cap	Nitrate ionophore in PVC	Selective binding of nitrate ions by ionophore	Myers et al. 2012
	Chloride ion	ZnO nanorods	AgCl thin film	Anodization	Chu et al. 2010b
	Ammonium ion	Gan cap	PVC enriched with nonactin	Selective binding of ammonium ions by ionophore	Alifragis et al. 2007b
	Oxygen gas	GaN	Indium zinc oxide	Oxidation	Wung et al. 2010
	Hydrogen gas	Pd-MOS Schottky structure	None	Catalytic dissociation	Cheng et al. 2006; Hung et al. 2012b
	Cl_2 gas and HCl vapor	Pt	None	Actions of oxidizing and reducing gases on Pt-gate	Son et al. 2011
HEMT-based biosensors	DNA	Au	Thiolated ssDNA	Hybridization	Thapa et al. 2012
	Glucose	ZnO nanorods	Go_x	Enzyme promoted reaction	Chu et al. 2010b
	Lactic acid	ZnO nanorods	LO_x	Enzyme promoted reaction	Chu et al. 2008
	Uric acid	ZnO nanotetrapods	Uricase	Enzyme promoted reaction	Song et al. 2012
	c-erb-2	Au	Antibody (Ab)-c-eb-2	Antibody (Ab)-Antigen (Ag) binding	Chen et al. 2008
	PSA	Au	Ab-PSA	Ab-Ag binding	Kang et al. 2007
	KIM-1	Au	Ab-KIM-1	Ab-Ag binding	Wang et al. 2007
	P. Marinus	Au	Ab-P.Marinus	Ab-Ag binding	Wang et al. 2009
	Botulinum	Au	Ab-Botulinum	Ab-Ag binding	Wang et al. 2008

Interesting areas of ongoing/future research include:

(i) High-pressure sensors that are capable of performing reliably in uncooled condition in extremely severe conditions, such as aircraft wings, combustion engines, exhaust gas pipes, etc. (ii) HEMT-embedded micro-accelerometers based on the electromechanical coupling effect of GaAs HEMT structure have high sensitivity and good linearity, providing a new test method for micro-gravity, micro-displacement, pressure and other parameters (Jing et al. 2009, Jia et al. 2010). (iii) GaAs HEMTs embedded at the root of cantilevers improve the sensitivity to external force (Hou et al. 2010). This research will promote the development of a novel sensor technology. (iv) HEMT device downscaling in terms of both the gate length and the vertical architecture further expands the operating bandwidth into the terahertz gap (electromagnetic spectral range from 0.05 to 20 terahertz) for supporting futuristic sensing and imaging applications along with power diminution for autonomous distributed sensor networks. This will help in harnessing an intriguing but so far elusive stretch of the spectrum offering considerable opportunities for exploitation. (v) Pollution caused by the burning of fossil fuels can be reduced by ensuring efficient combustion processes. Careful monitoring of exhaust gases with real-time feedback control enables corrections to be made in a timely fashion. Research efforts must be made on developing trustworthy sensing technologies for real-time monitoring of combustion processes and exhaust gases, which are challenging to assess, e.g., a GaN HEMT-based soot particulate sensor for the combustion exhaust gas environment, or a HEMT hydrogen gas sensor for monitoring emissions from hydrogen-fuelled vehicles, affording examination of sensor output from remote locations. (vi) SAW-HEMT design concept of chemical gas sensors applies two different sensing principles, based on SAW (surface acoustic wave) and HEMT (Lalinský et al. 2010), which can represent a new generation of devices appropriate for the multifunctional monitoring and detection of gases and toxic volatile chemicals. (vii) Handheld, programmable, single-chip, noninvasive rapid diagnostic sensors for detecting early signs of medical problems in humans is an exciting research area offering unlimited possibilities (Ren et al. 2011). Being capable of wireless communications, these sensors are useful, for not only real-time monitoring of patient health but also fast detection of toxins in the environment, strengthening significantly our responding ability. Sensing and identification of biological agents is more complex than chemical agents because many symptoms in incipient stages are frequently comparable and nonspecific, making the need for fast identification obligatory.

But the investigations made so far have been of exploratory nature. Repeatability of developed processes and their up-scaling to manufacturing requirements need to be examined. Long-term reliability studies of these microsensors are necessary to establish them as commercial products. Challenges faced in widescale commercial adoption of HEMT biosensors are (Kang et al. 2008): (i) The problem of stability of surface functionalization layers during long-term storage, restricts the application of some sensors outside hospitals. (ii) Higher sensitivity for certain antigens like prostate or breast cancer will permit sensing in body fluids excluding blood, e.g. urine and saliva. (iii) Like enzyme-linked immunosorbent assay (ELISA) test, a sandwich assay allowing the estimation of the same antigen with two different antibodies must be investigated. (iv) For catering to simultaneous detection of several analytes, multiple sensor integration on a single chip and multiple signal processing capability, together with automatic microfluidics and associated software are necessary. (v) Packaging technology amenable to a low-cost marketable device is required.

Nonetheless, the opportunities are immense and applications are colossal. Research efforts continue to explore new avenues.

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